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# A METHODOLOGY TO PREDICT TRANSIENT ENGINE COMPARTMENT AIR TEMPERATURE FOLLOWING ENGINE SHUT DOWN[1]

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**ABSTRACT**

*Cooling and heat protection of the engine compartment significantly impact the performance of combat vehicles. An increased heat load occurs during soak-back after engine shut down, where the fans are shut down. Heat is transferred from the hot components in the engine compartment by natural convection to the surrounding air and by radiation to the armor. The heat is then dissipated to the ambient mostly by convection from the outside surfaces.*

*The objective of this study is to develop a methodology to predict the engine compartment airflow velocity and temperature distributions, as well as the surface temperature of critical engine components following engine shut down. This study was conducted using a full-scale, mock-up engine compartment of a typical wheeled combat vehicle under steady-state and transient operating conditions. The Computational Fluid Dynamics (CFD) package Fluent was used to conduct the simulation. Steady-state simulation was performed first to predict the condition prior to the soak-back. A transient simulation was then performed to predict the flow and temperature fields during soak-back.*

*The developed methodology includes the creation of a conjugate heat transfer model. During soak-back, the stored thermal loads from the engine, transmission, oil pan, and exhaust system start to transfer to the air in the engine compartment by natural convection. This causes a temporary rise in air temperature of the engine compartment environment. This temperature rise causes more heat transfer to the crew compartment. It could also damage thermally sensitive components by approaching their critical design temperature. The engine compartment air temperature starts to drop following the temporary rise until temperature equilibrium is achieved. The rate of the reduction in temperature and the time that is required to reach thermal equilibrium depends on the ambient air temperature and wind speed. A significant advantage of this analytical methodology is that no physical model is required.*

## INTRODUCTION

Cooling and heat protection significantly affect the performance of ground vehicles. As more components are packaged in the same space of the engine compartment and the power demand is increased to drive these components, predicting the thermal behavior of the engine compartment, therefore, becomes necessary in designing a vehicle.

The above scenario is amplified in combat vehicles where the cooling of the powertrain and the ventilation of the engine compartment become essential to the performance of many critical systems and components located within the engine compartment.

The objective of this effort [1] is to develop a methodology to predict the engine compartment flow and thermal distribution following engine shut down. Specifically:

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- The airflow distribution (velocity components).
- Air temperature distribution in the vicinity of hot surfaces.
- Temperature on the surfaces of the engine block, transmission, intake and exhaust systems, as well as other components.

This study was conducted for a full-scale, simplified engine compartment of a representative wheeled combat vehicle undergoing steady-state and transient operations.

Steady-state simulation was performed to predict the vehicle thermal condition prior to “soak-back” (also referred as after boil). A transient simulation was required to predict the flow and temperature distribution during soak-back. Soak-back (or after boil) refers to the time period from engine shut down to the point when the engine compartment reaches thermal equilibrium (i.e., no further increase in temperature).

Prior to soak-back, the vehicle may endure high thermal loads due to performing a sequence of demanding mobility conditions such as highway driving and grade loads in hot environment with ambient temperature > 95 °F. Due to absence of any forced airflow in the engine compartment from the fan or surrounding ambient during soak-back, the flow in the engine compartment is driven by buoyancy [2, 3]. During soak-back, the stored thermal loads from solid parts (i.e., engine, transmission, oil pan, and exhaust system) start to transfer to the air in the engine compartment by natural convection. This causes a temporary rise in temperature of engine compartment environment. This temperature rise in the engine compartment may cause coolant overflow and more heat transfer to the crew compartment. It could also damage some thermally sensitive components by approaching their critical design temperature.

The engine compartment air temperature starts to drop following the temporary rise by convecting and radiating heat to the ambient until thermal equilibrium is achieved. The rate of the reduction in temperature and the time that is required to reach thermal equilibrium depends on the ambient air temperature and wind speed.

## BACKGROUND

The existing methods for designing the cooling system for a ground vehicle include extensive testing and analysis under various mobility conditions. Testing is usually made up of wind tunnel and road tests such as maximum velocity, uphill grade, and idle conditions. Analytical techniques utilize numerical simulations to perform steady-state analysis for predicting the airflow and temperature fields of the thermally sensitive components through the engine compartment. One of the advantages of analytical techniques is that no physical prototype is required. In addition, quick and cost effective “what if” investigations can be carried out in order to optimize the design.

The vehicle experiences heat loads during normal operation and duty cycles. However, an increased heat load occurs after engine shut down, during soak-back. After engine shut down, the fans shut down, and cooling of the engine compartment occurs mostly by natural convection. Heat is transferred from the hot components in the engine compartment by natural convection to the air in the engine compartment, and by radiation to the armor, which essentially are the walls of the engine compartment. The heat is then mostly convected away from the outside surface of the armor to the ambient.

This study focuses on the methodology to simulate the thermal conditions within the engine compartment during soak-back.

## METHODOLOGY

A methodology is developed to simulate the vehicle soak-back and compute engine compartment temperatures. This methodology met the objectives of this study by creating a Computational Fluid Dynamics (CFD) model with conjugate heat transfer.

The developed methodology is outlined in the following steps:

- ➢ The engine thermal loads are computed from a 1-D powertrain simulation code (GT-POWER) to determine:
  - Engine heat flux.
  - Transmission heat flux.
  - Exhaust system heat flux (turbocharger, manifold, and pipes).
- ➢ The steady-state condition is imposed:
  - The thermal loads are applied to the engine, transmission, and exhaust system.
  - The ventilation fan is on with airflow rate of 700 CFM.

- The conjugate heat transfer and radiation heat transfer are calculated.

➢ The temperature distribution from the steady-state simulation is computed for:
  - Engine compartment walls.
  - Armor (internal and external walls).
  - Surfaces of other components in the engine compartment such as the shock towers, intake manifold, pipes, blower, and electrical component.

➢ The transient simulation (soak-back and cool down process) is performed:
  - The engine is turned off and thermal loads are removed from engine, transmission, and exhaust system.
  - The fan is turned off.
  - Results of the steady-state simulation are used as initial condition for the transient simulation.
  - The simulation is run for one hour after engine shut down.

➢ The temperature distribution from the transient simulation (i.e., temperature rise and cool down) is computed for the engine compartment airflow and critical components surfaces residing within the compartment.

## MODELING AND SIMULATION DETAILS

The methodology is described in the flow chart shown in Figure 1. Simulation of vehicle soak-back requires a CFD flow model and boundary conditions

In this project, a full-scale simplified generic vehicle flow model was constructed; no real vehicle CAD was utilized. This generic model is similar to size and shape to a typical wheeled combat vehicle engine compartment. In order to simulate thermal soak-back, a conjugate heat transfer model must be constructed. The model includes all major components residing in the engine compartment such as the engine, turbochargers, exhaust manifolds, exhaust downpipes, heat exchangers, air induction system, shock towers, fans and blowers, and reservoirs, which block the flow or affect the temperatures. The CAT 3126 engine was placed into the engine compartment and segmented into areas of discrete temperature distributions: cam cover, intake region, exhaust region and oil pan.

The flow model is essentially a virtual wind tunnel, which contains the engine compartment; as shown in Figures 2-4. The CFD package Fluent Version 6.3 [4] was used to perform the fluid flow and thermal analysis simulation. The model contained more than 7 million volume cells. Boundary conditions were obtained from the operation of similar diesel engine.

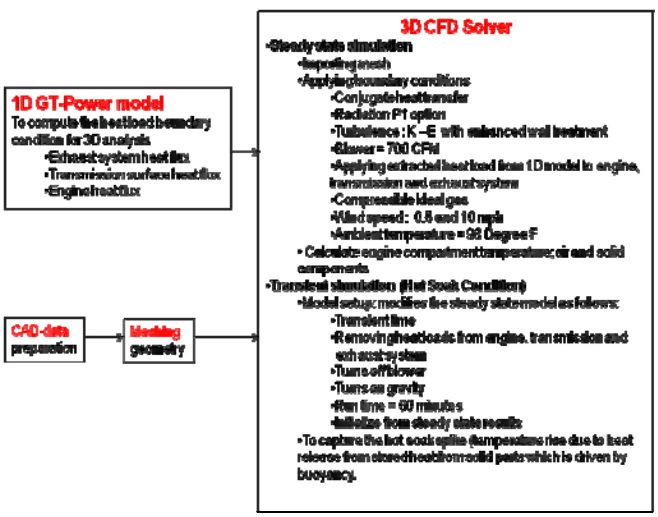


**Figure 1: Methodology flow chart.**

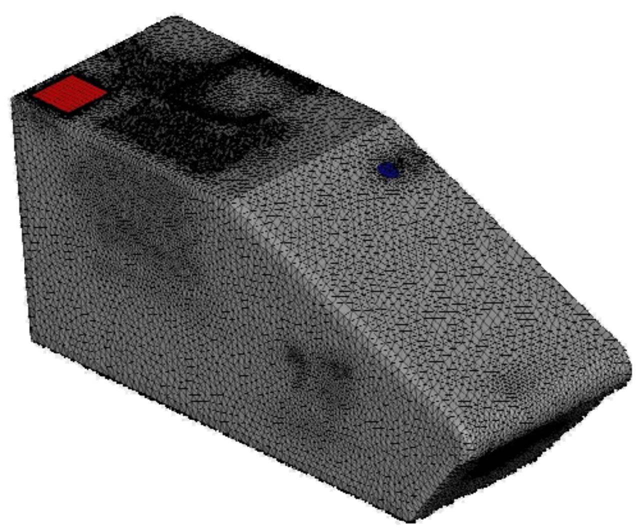

**Figure 2: The engine compartment flow domain.**

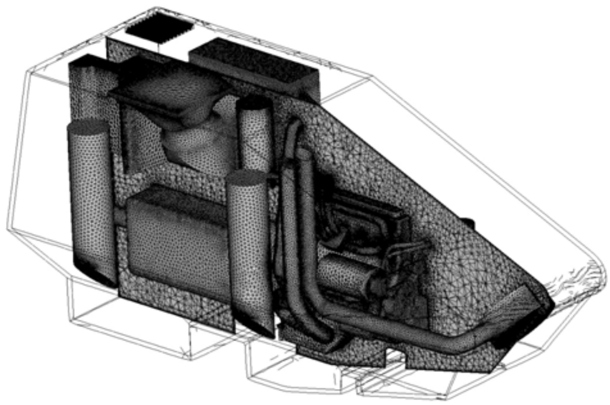

**Figure 3: Sections through engine compartment flow model.**

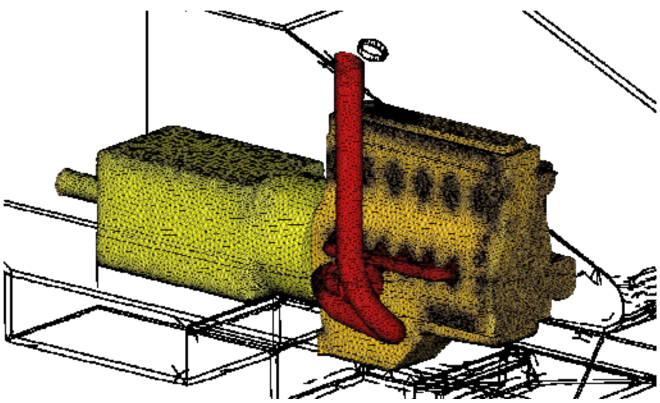

**Figure 4: Engine surface mesh.**

The discretization of the flow domain in the engine compartment must be fine enough to resolve the natural convection flow structure that occurs due to thermal gradients. In order to capture the thermal boundary layer correctly, ten prism layers were created on the internal and external walls of the engine compartment. The first prism cell height was 0.15 mm with the growth ratio of 1.2. Figure 5 shows the details of the boundary layer grid near the engine compartment wall.

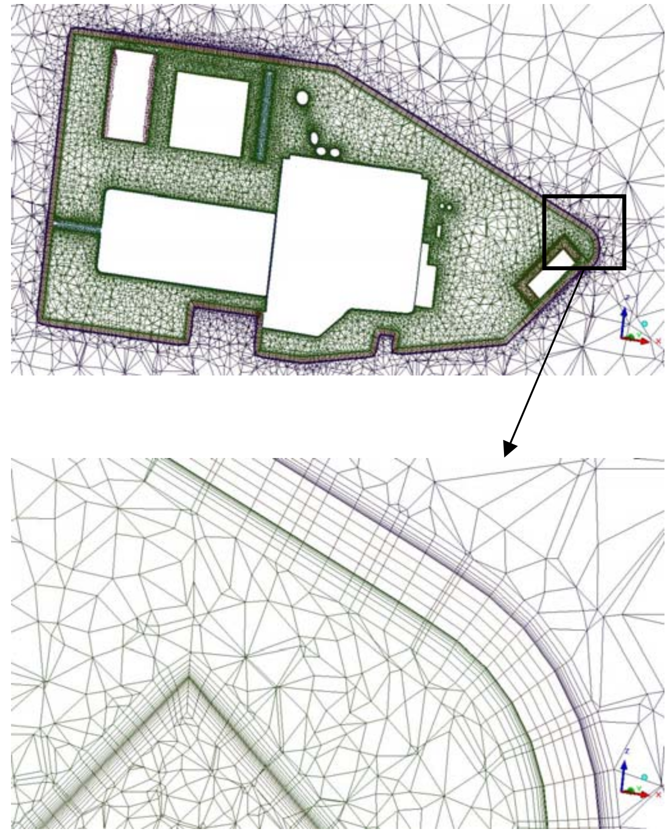

**Figure 5: Prism layers on the walls.**

**RESULTS**

The soak-back analysis is composed of two simulations: steady-state condition and transient soak-back. The steady-state simulation is performed to calculate the initial conditions and boundary conditions for the transient soak-back simulations.

The model set up for the steady-state simulation is outlined as follows:

- Solver:
  - Pressure-based Navier-Stokes equations.
  - Steady-state simulation.
- Turbulence model:
  - Standard k-Epsilon model.
  - Near-Wall Treatment.
  - Enhanced Wall Treatment.

- Ideal gas with buoyancy.
- Energy equation.
- Radiation model:
  - P1 option of P-N model.
- Boundary conditions:
  - Velocity at inlet (0.5 and 10 mph).
  - Pressure at outlet.
  - Ventilation fan flow rate (700 CFM).

The thermal loads must be applied as heat sources since the combustion in the engine is not simulated. This data can be obtained from experimental or numerical analysis (1-D simulation such as GT-POWER). Table 1 describes the heat sources that were used in this steady-state simulation for an engine similar to the Caterpillar 3126 diesel engine.

**Table 1:** Heat source for an engine similar to Caterpillar 3126 diesel engine.

| Source Component | Heat Source (W) | Surface Temperature ($^oF$) |
|---|---|---|
| Engine | 2100 | 280 |
| Transmission | 1800 | 260 |
| Exhaust Manifold | 2500 | 1225 |
| Exhaust Pipes | 500 | 1070 |

The temperature distribution was computed from the steady-state simulation for the following components:

- Engine compartment walls.
- Armor.
- Surfaces of other components in the engine compartment such as the shock towers, intake manifold, pipes, blower, electrical component, and cooling package component.

The transient soak-back simulation set up is similar to the steady-state simulation with the following modifications:

- Time is set to transient.
- Heat load is removed from engine, transmission, exhaust manifold, and exhaust pipe.
- Ventilation fan is turned off.
- Gravity is turned on.
- Run time is set to 60 minutes.
- Steady-state solutions are used for initialization of the transient solution.

In this study, the transient simulation was performed at two wind speeds: 0.5 and 10 mph. These values were chosen to assess the impact of wind speed on engine compartment cool down time.

Figures 6 through 8 show the temperature history of maximum temperature of external armor, engine compartment air temperature and mass averaged air temperature of the engine compartment, respectively. These results are for the 10 mph wind speed simulation.

Figure 8 shows that the mass averaged engine compartment air temperature experiences a sudden rise by 20 °F and then slowly starts to cool down. It is evident that the engine compartment temperature reaches a maximum value within 7 minutes after engine shut down and begins to stabilize in about 8 minutes as the engine compartment environment approaches thermal equilibrium.

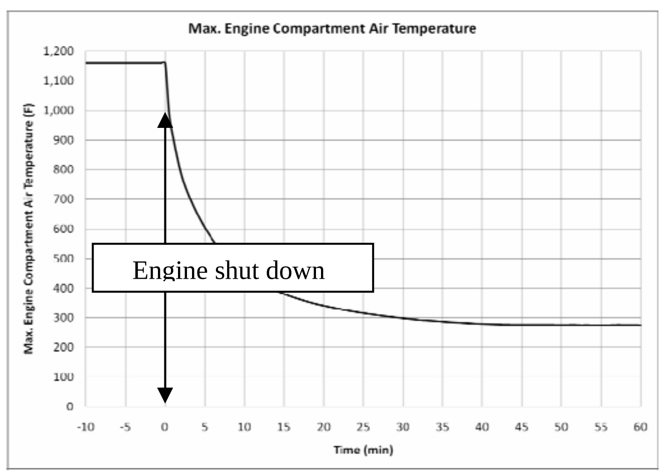


**Figure 6: Maximum temperature on the external armor surface.**

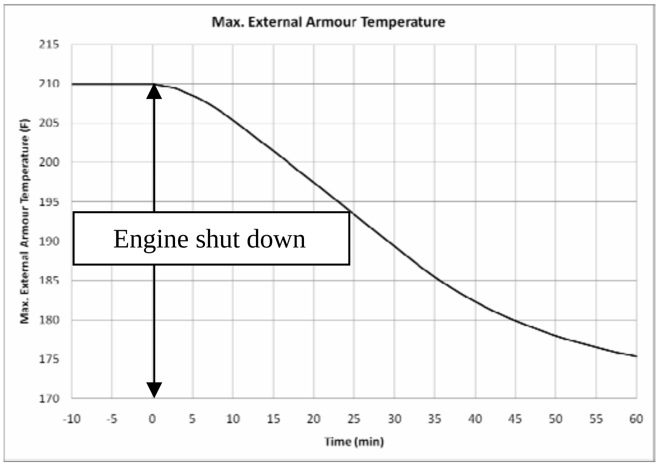


**Figure 7: Maximum engine compartment air temperature.**

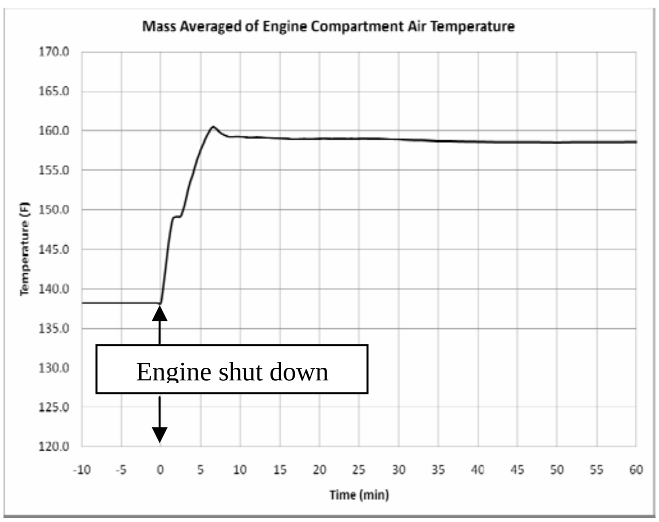


**Figure 8: Mass averaged air temperature of engine compartment.**


## SUMMARY

A methodology was developed to predict the engine compartment temperatures during vehicle operation and after engine shut down. The vehicle geometry was generic for this study and the boundary conditions were based on an engine of similar size. However, any temperature test data from the actual engine compartment measurements will help validate this methodology.

Results demonstrate that Computational Fluid Dynamics (CFD) can be successfully used to simulate the flow and thermal fields within the engine compartment both at steady-state and transient operations. The methodology can be applied to current and future vehicle programs to predict the critical temperatures within engine compartment, including engine walls, components, armor, and air temperatures. In addition, this methodology can help determine the ventilation strategy for engine compartment during engine operation and after engine shut down.


## REFERENCES


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